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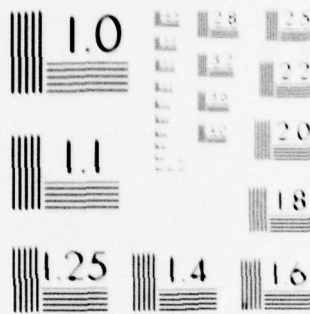   MAR 79 A V SERYEBRYAKOV
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The chapter discusses the various artifical and environmental factors affecting river flow: floods, dams, reservoirs, channel bed and water surface gradients, dredging, locks, tides, ice, tributaries, sediment load, water temperature, and annual, season and diurnal variations in water levels and current velocity. Examples of many Soviet rivers are given: Don, Dnieper, Irtysh, Volga, Oka, Kama, Donetz, etc. and others.

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Contents

A. V. Seryebryakov

Chapter I

Hydrologic Regime of Rivers in the Tailraces of Dams

From time immemorial, man has been using water for transportation, as a source of energy, as a natural defense line against enemies, etc. The water supply of the Earth is enormous. However, the distribution of water resources on the face of the Earth and in time is quite irregular. Different types of hydraulic structures must be built to redistribute water resources and use them more fully in the national economy.

Hydraulics has been a branch of engineering for many centuries. However, hydraulic works designed to influence channel formation processes were begun only in late XIX century. The first studies of estuary processes also belong to this period. The works of Dubois (1873), who wrote mathematical equations expressing the "drag force" of detritus, and by Farge, who determined the first laws of river channel structure and development, should be mentioned. In order to solve the practical problem of how to define a navigation channel, Girard analyzed internal currents of flow within a river bend.

One of the founders of free river hydraulics, V.M. Lokhtin, proved in the late XIX century [43], that the type of river channel development is closely related to the features of geographic environment. As a first approximation, he postulated three factors that determine the features of a specific river (water content, gradient, and river bed erosion rate) and provided a well-known expression for the coefficient of channel stability. Lokhtin determined how channel bars (shallows) form and grow and proposed a method for improving navigation conditions in shallow reaches by building correctional structures in the channel.

Immediately following Lokhtin, N.S. Lelyavskiy noted [40] the peculiarity of channel forming mechanisms - how configurations (shapes) of a channel direct the flow of river currents, but are themselves affected by the distribution of these currents. This dialectical interrelationship of channel and current is the basis of the modern science of channel processes. Lelyavskiy like Lokhtin, realized the need to study channel processes in nature, without which it would be impossible to find a theoretical solution for the problems of river hydraulics.   8

Later, as dredging technology developed, V.G. Kleyberg studied the peculiarities of river channel formation during seasonal changes of water levels and established and proved in practice (on the Volga) how to maintain navigable depths in rivers by transit dredging. This method, which consists of preventive dredging of navigation channels in shallow regions during the

high water period, was widely accepted.

The proponents of dredging did not renounce the theory of channel processes, but continued to develop and improve it. For example, the idea of artificially inducing secondary currents in a stream is Kleyberg's, while another adherent and theoretician of dredging, V.Y. Timonov, established the first river channel hydraulics laboratory in Russia.

The detailed study of channel processes in field and laboratory, as well as the accumulated practical results of work on rivers constituted the beginnings and development of the modern method of improvement of navigation conditions on the rivers. This method consists of dredging operations in shallow areas that provide the necessary channel shapes, while the stability of this configuration is maintained by building a system of structures to control the movement of water and detritus.

Many studies of channel processes have been made by Soviet and foreign scientists in recent years. Contemporary theory and practice of river channel hydraulics makes it possible to establish a well enough founded theoretical explanation of the variations of channel processes in rivers after their flow is regulated by large water reservoirs.

The theory of channel processes deals with currents whose unstable structure results from continuous variation of the river channel shape. The gradually progressing erosional-depositional processes actively influence channel formation conditions, but channel processes, which result from change in the stream structure, progress much more slowly than variations in river flow. Consequently, a situation where the stream moves through a channel whose shape still conforms to the preceding phase of the river   9
flow, is typical. Under uncontrolled river conditions, the channel reformation process never reaches the stage of complete correspondence between the stream and the channel. The cycle of formation and elimination of this incongruency is an inherent peculiarity of the channel process.

Correct quantitative and qualitative evaluation of channel processes can be obtained only through analysis of current structure. Variations of current structure result from variations of its quantitative parameters through time. In addition, this structure is also influenced by changes in channel shapes (configuration). Consequently, formation of a channel can be viewed as the result of interaction of individual conditions of the stream and channel. The water flow is the part of the channel process that determines the qualitative aspect of the stream, while the channel with its features is the form of the process. Being dependent on the stream, the shape of the channel actively influences the content of the channel process, but is relatively stable (independent), even when the character of the internal currents of the stream changes. This latter feature explains the lagging of channel process behind changes in the stream structure.

The state of the channel is determined by its morphologic parameters, among which are width (B), depths (T), top-view shape characterized by the radius of curvature (R) and ratio (B/R), cross-sectional shape (T/T max, T/B, T/R), type of flood bed, etc. The stream is characterized by the indices of its movement, among which are Reynold's number (Re), Froude

number (Fr), gradient (I), turbidity (p), temperature (t^o), etc. At any moment in time, in any sector, the channel process is determined by the simultaneous interaction of all the listed parameters and many other hydrologic, hydrodynamic, and morphologic factors.

On different rivers, under different specific conditions in time and space among the multitude of continuing interactions, there are the main interactions, which determine the main direction and dimensions of channel processes, as well as secondary interactions. The problem of the researcher has been reduced to determination of the main interactions by mean of an analysis made under specific conditions and, knowing these conditions, causing the channel process to develop in the desired direction through appropriate hydrologic measures. The transformation of the main interactions into secondary ones and vice versa is quite possible in a channel process, as in all natural processes. For example, channel deformations of regulated rivers are significantly influenced by such factors as modification by floods (general pattern) and diurnal regulation of the flow by hydroelectric works (individual feature of the sector near the dam). When diurnal water level fluctuations are insignificant in the tailrace and the temporal variation of the discharge (2Q/2T) is low, diurnal regulation of the flow only slightly influences the channel process; during large diurnal water level fluctuations and correspondingly significant values of 2Q/2T, diurnal regulation of the flow can become the determining factor of channel formation near the dam.

Individual features can be the determinant in river channel formation
in certain reaches, but this does not mean that knowledge of such features allows one to discard the general rules of channel formation. Knowledge of individual peculiarities is only a necessary supplement for more exact determination of the general rules applicable to specific conditions.

In order to provide theoretical bases for the continuing reformation of a river channel, one must use only the common method of analysis of the channel processes themselves, but also synthesis of thoroughly studied individual factors that influence channel formation. For rivers with regulated flow, such a complex method seems to be the only feasible one, because on such rivers initial data for general morphologic analysis are quite often insufficient. At the same time, creation of large reservoirs on these rivers causes a considerable alteration of their channel regime. There one should mention N.J. Makkaveyev's conclusion that "ateration of the flow regime from the water shed territory leads to alterations of river relief, just as the building of structures that mechanically influence the stream."

2. Water Flow Regime

Under conditions of the socialist planned economy, large water reservoirs created on rivers with significant average annual water flow are designed to solve complex energy, improvement, water transport, and other problems. In spite of the frequent appearance of conflicts of interest of individual branches of the national economy in the use of river water resources, the main purpose of regulating river flow is the same. It is the storage of river flood discharge for later efficient use. At present, the creation of large water bodies for a single purpose with-

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out resolving the complex of other problems is unthinkable. Thus, modifying flow regimes is similar in the outfalls of all large reservoirs.

Current hydraulic construction is characterized by an increase in the size of hydraulic structures and reduction in their construction time. As the sizes of these structures increased, their influence on the hydraulic and channel regime of the river increased sharply. This can clearly be seen from analysis of changes in the hydrologic regime in the upper and lower sections of reservoir of different volumes. For example, after construction of the Volkhovskaya Hydroelectic Station (HES), because of the small size of the structure and the reservoir created by it, changes in the ice breakup, flood progress, and river load regime in the upper and lower ends were insignificant. The reservoir created as a result of construction of the Dueproges HES (Lake Lenin), although this reservoir contains less than 10 percent of the average annual Duiepr River flow, caused very significant changes in the natural regime of the river. The ice regime at the upper end (of the lake) and below the dam was changed completely. The stream temperature regime changed and water entering the tailrace was discolored.

Figure 1. Graphs of average long-term characteristics of a stream before (solid line) and after (dashed line) regulation of the river flow.
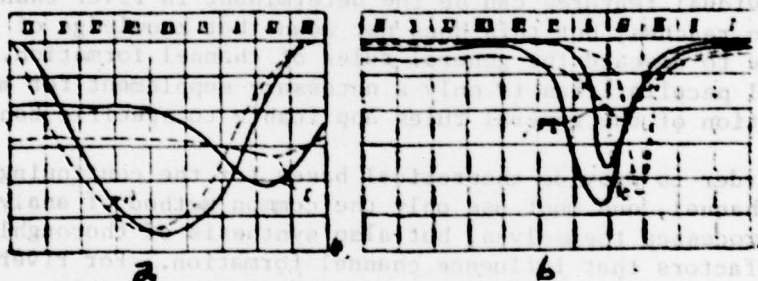
a. Water and load discharge;
b. Gradients of free water surface and stream temperature

Large modern reservoirs on rivers are comparable in size (volume) to the total mean annual flow. Such water bodies, not only completely regulate the water and ice flow regimes of their rivers, but also drastically change their load and thermal regimes.

An example of changes in the main hydrologic parameters of a stream due to regulation by a large reservoir is shown in figure 1, which gives graphs of average long-term water discharge (Q), sediment load discharge (Q_{TB}), surface water slope (I), and stream temperature gradient (t^o) for one of the hydraulic sections of the Don River (based on Hydrometeorological Service data). Curves showing events prior to construction of the Tsimlyansk reservoir (on the Don) appear as solid lines, dashed lines depict events after the construction of this reservoir.

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Most hydroelectric stations belong to intergrated energy systems that include thermal and other (types of) electric power station. They work under varying loads during any one day and are subject to the so-called "sharp peak regime." Their load increases sharply during the peak hours of energy consumption and drops to a minimum during the rest of the day. Such a hydroelectric station operation cycle causes a distinctive irregular flow in the 30 to 50-km section of the river downstream from the hyralic structure that is characterized by periodically recurring and rather steep waves representing the maximum water release period. In winter, the reservoir usually makes it possible to pass water through HES turbines at an average discharge rate that is several times higher than normal. The irregular regime of the stream and the increase in winter water flow creates a drastically different regime from the normal hydrologic regime of the river.

As the sizes of hydraulic structures increase, the volumes of the power prisms of the navigation locks also increase. These prisms become comparable to the volumes of the navigation channels adjoining the locks situated in the reservoir entrances and exits. Short, high waves are created in the channels by the filling and draining of the locks. These waves create additional navigational difficulties on the approaches to the lock - especially if the waves are superimposed on the diminishing water levels caused by the diurnal operation cycle of that HES.

These changes in the HES discharge depend less on the volume of the reservoir, than on the degress the reservoir regulates river flow, i.e. on the ratio (V/W'), where V is the useful volume of the reservoir and W' is the mean long-term flow during the spring flood. The ratio V/W' = B is called the index of degree of lfow regulation by a reservoir. Reservoirs are described in table 1, based on the degree of flow regulation.

The regulation capacity of water reservoirs in table 1 can be applied directly to the downstream river sectors only if there is a single reservoir. However, if there is a series of reservoirs above the given reservoir, the degree of flow regulation can be determined as the relationship of the useful volumes of all the reservoirs of the series (EV) to the mean value of the mean value of the flood flow in the hydraulic section of the lower hydraulic structure (W H). Both of the above values can be derived from table 1; the first is obtained by adding the useful volumes involved, while the second is the sum of the lowest hydraulic structure flood flow and the volumes of the upstream reservoirs.

For example, the degree of regulation of the lower Volga is B = 76.0/160.7 = 0.47, where 76 km^3 is the total useful volume of all the reservoirs of the Volga and Kama, while 160.7 km^3 is the calculated total flood flow into the Volgograd reservoir (94 km^3) and the useful volumes of all the upstream reservoirs (66.7 km^3), with the exception of Volgograd reservoir. For the Volga below Gor'kov hydraulic installation, B = 21.7/30.9 = 0.76, etc.

For a series of reservoirs, it is sometimes practical to determine the regulated flow, not in comparison to normal conditions, but compared to conditions prior to the construction of a given hydraulic installation. For

Table 1

River	Reservoir	Useful Volume V, (KM^3)	Flood Runoff W', (KM^3)	B
Volga	Vvan'kov	1.0	4.1	0.24
	Uglich	0.9	5.8	0.16
	Rybin	16.7	17.5	0.95
	Gor'kov	3.1	12.3	0.25
	Kuybyshev	34.5	122.1	0.28
	Volgograd	9.3	94.0	0.10
Kama	Kama	8.4	30.2	0.24
	Votkin	2.1	31.9	0.05
Don	Tsimlyan'	12.0	16.5	0.73
Dnieper	Lenin Lake	1.3	29.4	0.04
	Kremenchug	9.0	26.0	0.35
	Kakhov	7.6	30.2	0.25
Irtysh	Bukhtarmin	31.0	11.0	2.80
Ob'	Novosibirsk	5.0	25.0	0.20
Angara	Bratsk	28.4	38.4	0.73

example, the difference in construction dates of the hydraulic structures above Rybinsk and Gor'kov on the Volga is 15 years. Consequently, it would be more practical to determine the degree of regulation of the Gorodets-Gor'ki sector compared to the preceding fifteen years, i.e. to conditions existing after construction of the Rybinsk dam. Consequently, for this sector it would be more sensible to assume that B = 3.1/12.3 = 0.25, and not $\underline{14}$ 0.76, which includes all the upstream reservoirs. For similar reasons, the degree of regulated flow of the lower Volga should be compared with conditions after construction of Rybinsk dam and assume this to be 0.40 instead of 0.47, which includes all the upstream reservoirs.

Below we will discuss the river regime features in the outlets of reservoirs that, having a capacity comparable to the flood flow of their rivers (V > 0.1W'), not only redistribute the flow in time, but significantly alter the sediment load and temperature regimes of the stream.

The changes in the water flow regime are quite large, not only in the tailrace of the dam, but also at a considerable distance from the dam and even below the mouths of large tributaries. For demonstration purposes, table 2 contains long term mean ten-day water flow rates in the Rozdor hydraulic section of the Don River before and after flow regulation. This

hydraulic section is 150 km from Tsimlyan' dam and lies below the estuary of the tributary Severnyy Donets.

Table 2

Periods (yrs)	10-day periods	Monthly rates of water flow (m3/sec)											
		I	II	III	IV	V	IV	VII	VIII	IX	X	IX	XII
1943-51 before flow regulation	I	238	280	595	1721	3995	1064	351	269	232	220	254	279
	II	259	418	956	2186	3324	567	331	262	231	232	267	210
	III	258	454	1388	3185	1939	472	297	247	221	248	296	177
1952-1964 after flow regulation	I	390	518	693	1550	1370	906	680	620	595	620	617	551
	II	427	628	748	1608	1427	800	667	610	598	625	630	387
	III	548	764	865	1495	1109	728	649	602	580	615	670	396

The data in table 2 show that during any one year the distribution of flow varied mainly in the direction of a decrease in flood flow and a more even distribution of the monthly flow. If before regulation of the flow the ratio of the maximum to the minimum mean ten-day flow rate was 3995:177 = 23, then after flow regulation this ratio decreased to 1608:387 = 4.2; or a 5.5 decrease. The change in this typical value is the most important hydrologic feature of a regulated river and determines the alteration of the river regime as a whole. In a sector of a river located above the inflow of large tributaries, the change in the flow regime is even more perceptible. One should note that the increase in winter water flow results from the increase in the HES load. At Tsimlyan' dam, this increase is relatively small, doubled on the average. On other dams, the increase in winter water flow is much greater - 5 to 6 fold at Rybinsk dam and up to 3-fold at Kuybyshevsk dam.

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Figure 2 presents hydrographs for typical years before (dashed line) and after (solid line) regulation of the outlet flow of Tsimlyan' dam. The graph shows that during the flood period, the curves of regulated flow (solid lines) differ more than the curves of normal conditions (dashed lines). At the same time, the relative variation of higher water flow rates became less significant during the dry period; this can easily be deduced from comparison of the long-term mean daily water flow prism curves (fig. 3) for pre- and post-regulation periods. After flow regulation, the frequency rate of dry-period flow

increased so much that it can be adopted as the reference formative flow
recommended by N.I. Makkaveyev [50].

Figure 2. Hydrographs of typical years
before (dashed line) and after
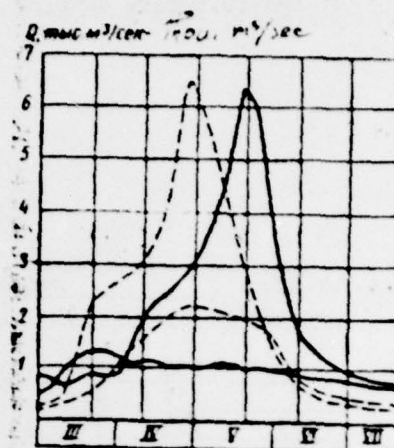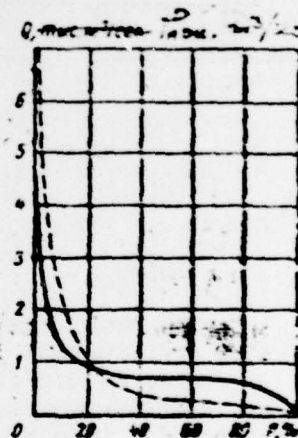(solid line) regulated flow.

Figure 3. Mean water flow prism
before (dashed line)
and after (solid line)
regulated flow.

The high degree of applicability of the reference formative discharge
increases the dependability of existing hydromorphologic and hydraulic
calculation methods in building structures on rivers with regulated flow.
One should note that in the Tsimlyan' reservoir (the above example) is
one of the highly regulated reservoirs.

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In Rybinsk reservoir, with an even greater coefficient of flow regu-
lation, the flow regime changes are even more pronounced. On the other
hand, in reservoirs with less regulated flow, the changes in the outlet
regime are less perceptible, but of the same character.

Figure 4. Hydrograph of a regulated
river with weekly control
of the HES load.

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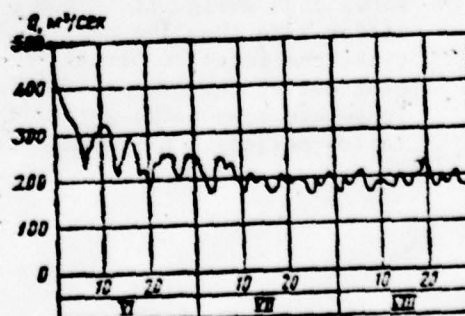
Diurnal and weekly regulation of flow is the feature of the water flow regime at the outlet of most dams. In figure 4 a example of weekly regulation appears in the form of the mean diurnal discharge graph of Pavlov HES on the Ufa River.

Observations made at the outlet of Gor'kov HES by the Volga Basin Route Service show that the weekly (water release) waves visible propagate for more than 300 km. The peak HES load regime is one of the serious, but practically unavoidable, inconveniences in navigation and exploitation of all types of water routes, ports, and other hydraulic structures, mostly due to intensive variations in water level and current speeds.

The 1950-51 and 1960-61 studies carried out by the Dnieper and Volga Basin Route Services at the outlets of Dneprov, Kremenchug, and Rybinsk HES, as well as regular observations of the Tsimlyan' HES (1953), showed that as one goes farther from the dam   the irregularity of the water flow at first decreases rapidly, but then the rate of attenuation decreases, and the diurnal (and even more so the weekly) discharge wave (with a small amplitude) propagates for several hundred kilometers, forming the so-called transient flow movement zone. However, a significant flow irregularity, characterized by the fact that the relationship $Q = f(H)$ is not unique and the individual points deviate from the mean value by more than $\pm$ 5%, is perceptible over relatively short distances from the dam. In the lower outlet of the Tsimlyan' HES, this distance is 20 km, while downstream from the Rybmsk HES outlet it is 50 km. The greater the absolute difference between the maximum and minimum water flow rates and their diurnal duration, the longer is the irregular flow zone.

The variable water flow regime of a river after flow regulation causes, in turn, changes in other hydrologic and morphologic characteristics of the river. In the literature, it is common to divide a river with regulated water flow into two zones; an irregular regime zone, within which the amplitude of water level fluctuation exceeds 20 cm; and an even-flow regime zone where the influence of diurnal regulation has no practical significance. A more thorough analysis of features of a regulated river regime shows that such a division is too arbitrary.

Because of the flatness of the diurnal regulation waves, the lower part of the unsettled regime zone differs very little, in the effect of stream action on the channel, from the settled flow zone. However, in the latter zone, the hydrologic and channel regime can be different due to the increasing influence of the downstream tributaries. In the estuary sector of the river, its regime depends mostly on marine influences. Consequently, farther downstream, we will adhere to our division of regulated rivers into four parts; the sector near the dam with clearly pronounced heterogeneity of $Q = f(H)$ relationship; stable flow regime sector above the confluence of a large tributary (including the lower part of the unstable flow zone); sector below the confluence of a large tributary; and (4) the estuary sector of the river.

3. <u>Surface Water Levels and Slopes</u>

On a regulated river, the water level regime varies depending on fluctuations of the flow regime. The frequency of high flood water levels decreases, while the frequency of higher level dry-period water levels increases. Winter water levels also increase considerably. For example, fig. 5 shows graphs of mean long-term water levels of the Volga River below Rybinsk HES before and after regulation by Rybinsk reservoir. For the flow regulation, we adopted the period before the exploitation of Gor'kov dam. These graphs show that the influence of reservoir flow regulation on the water level regime is significant downstream from the dam for more than 500 km, eventhough in this sector the Volga receives such large tributaries as the Unzha and the Oka, whose spring flow we will compare to the spring flow of the Volga. However, the influence of the tributaries is significant, <u>18</u> as can be seen from the graphs for the Yaroslavl' (above Unzha estuary) and Chkalovsk (below Unzha estuary) stations. On the other hand, on sectors without tributaries, the regulating influence of the reservoir is especially evident and depends very little on the length of the sector. For example, after construction of the Volgograd dam, the water level variation on the lower Volga is entirely similar at all stations from Volgograd to Astrakhan', a distance of 600km.

Figure 5. Graphs of mean water level on different hydraulic sections of the Volga below Rybinsk HES (dashed line 1916-1940; solid line - 1941-1953).
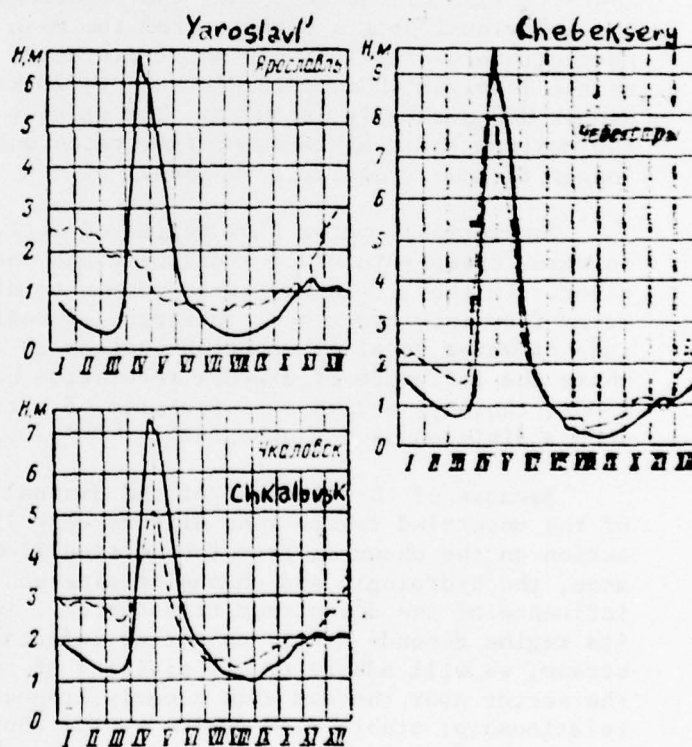
Regulation of the flow is even more noticable on the Sredniy (Middle) Irtysh, where there are no large tributaries for 1,500km from Bukhtarminsk HES to Omsk. This phenomenon is well illustrated in the report written by V.V. Degtyarev and G.F. Gusev [16].

The distinguishing feature of the water level regime of a regulated river is a significant decrease in the period of flood subsidence and, almost complete elimination of the shallow downsloping part of the water level curve that is typical of free plain rivers. This is significant in the formation of the dry season river channel. On free rivers, the flood decrease period is used to prepare for redredging the channels through shallows (bars). Certain peculiarities of the water level regime are also observed during the postautumn and prespring periods on regulated rivers. Intelligent use of these features is very important in navigation.

The special 1964-66 studies of hydrologic and ice regime features of the water routes of the RSFSR (Russian Soviet Federated Socialist Republic) showed that, during the postautumn period, water levels on regulated rivers exceed the reference dry season water levels, whereas under normal (natural) conditions, water levels often decrease during this period. An exception is the lower Don. Water levels in Tsimlyansk reservoir during its permissible operation regime have been based on calculated long-term conditions of regulated flow. In fact, the reservoir has not had enough water during 50% of the years to maintain normal navigation conditions below the dam.

Water levels are lower than reference dry season levels in some years during the prespring period on sectors directly below the dam (up to the tributary flood backwater extinction zone). However, lower levels can easily be eliminated if some changes are made in the flow regulation rules. Analysis of the water level and flow relationship curves $Q = f(H)$ for most hydraulic sections of regulated rivers, excluding sectors near the dam, indicates that these curves are close to those before regulation of the flow. However, there are some differences. For example, after several floodless years and, consequently, some convergence of the depths in deep and shallow sectors of the river channel; a slight subsidence (to 10-20 cm) of the $Q = f(H)$ curve is seen. However, after a subsequent high flood, the longitudinal river bottom profile became uneven again and the $Q = f(H)$ curve assumed its former shape. Therefore, one may assume that after flow regulation, as under normal conditions, water levels may vary at a given volume of water discharge which level is determined by the variation in water level during the flood period. It should be noted, that this process is observed, not only on hydraulic sections far from the dam, but can also occur near it. Figure 6 shows $Q = f(H)$ curves for different years below Gor'kov dam, based on standard observations processed by P.A. Lisovskiy. Similar graphs are also presented for the sectors below Novosibirsk (6,b) and Tsimlyansk (6,c) dams. The downslope of the $Q = f(H)$ curve results from the increase in channel volume below the dam and is clearly perceptible only in the lower part of the curve, i.e. during low water conditions.
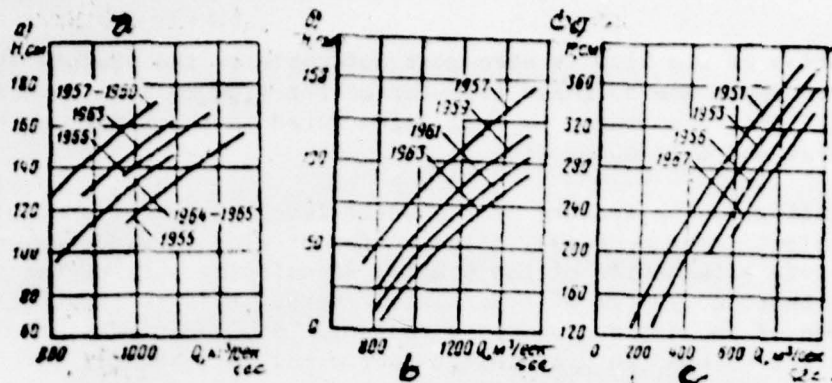
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Figure 6. Annual variation of Q = f(H) curves for the reaches below Gor'kov (a), Novosibirsk (b), and Tsimlyansk (c) dams.

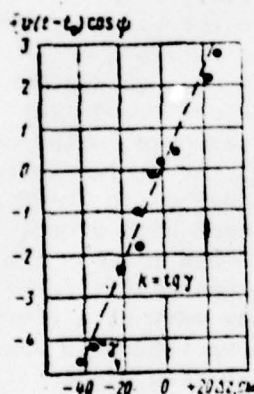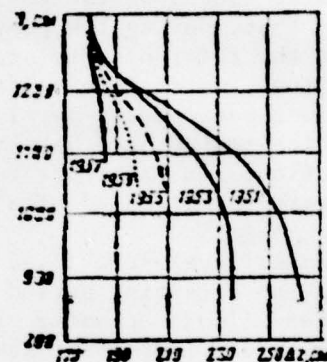**Figure 7.** Annual variation of A_Z = f(H) curves for sector of the Don River near the dam. →

← **Figure 8.** ΔZ = kv(t-to) cos curve.

This fact can be easily deduced from figure 7, which is a graph of Z = f(H), the relationship of the water level drop for the river sector near the dam to the water levels of different years of flow regulation.

Because of steep waves below hydroelectric stations (HES) operating in peak regime caused by diurnally regulated flow, the relationship Q = f(H) becomes multi-valued there, because water flows which correspond to the same water level, but occur during different stages of its rise or fall, are significantly different. According to V.A. Galkov's observations below Kremen'chug

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HES, whose regime is characterized by a sharp peak load, at the same water level mark, the water flow was 5,000 m^3/sec during the water level rise and 2,200 m^3/sec during the drop. During a stable regime this water level corresponded to a discharge of 4,000 m^3/sec. Such variations of water flow at the same water level are caused by variation of the free water surface slope during the rise and fall of the water level. In the example given, during the water level rise the slope increase is 2.5 times that observed during a stable regime. On the other hand during the water level drop the slope decreases almost to zero.

On the average, some decrease in dry season water slopes caused by the drop of the Q = f(H) curve is typical for the section near the dam. In the other parts of a regulated river, the slopes increase significantly during the dry period. In spring, the slopes even out to some degree and their values approach those of the dry period. Consequently, during the navigation period the slope typically becomes more even below the dams of regulated rivers. An exception are the river reaches above the inflow of tributaries. As the flood moves down the tributary, the slopes in these reaches decrease significantly due to the decrease in water flow through the dam cause by the backwater created by the tributary flood at the confluence with the main stream.

Significant variation of the water level and slope regimes is observed near the estuary sectors of the rivers. The pre-estuary sector of a river is a sector where the slopes of the free water surface decrease noticeably toward the estuary. The pre-estuary sector can be more than 100km long. During the flood period, slopes increase in the estuary sector; at the same time, the greater the distance over which steep slopes extend in the direction of the sea, the greater is the river flow during this period.

These fluctuations and the corresponding water surface slopes created by them depend mainly on the speed, direction, and duration of winds. Special standard measurements with more frequent, three-hour observations (during Q = const.) made in the channelized Alitubsk region of the lower Don (80 km from the estuary) revealed a statistical relationship between the water level accretion values Δ_Z and the water level during calm weather and at different wind speeds and durations in a given direction. As shown in figure 8, this relationship is guite clear. Its equation can be written as follows:

$$\Delta Z = kv \, (t-t_0) \cos \psi$$

Where ψ is the angle between wind direction and the river channel axis.

Prior to construction of the Tsimlyansk dam, wind-generated tidal water level fluctuations were observed along a 150-km sector (up to Melekhovskaya village). The amplitude of these fluctuations reaches 4m, while diurnal water level fluctuations during rapid changes in wind speed and direction exceeded 1.5 m.

After the Tsimlyansk reservoir regulated the river flow and consequently increased the dry season water flow, slopes increased near the estuary of the

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Don, and although this increase in mean slopes is not, in itself, very significant when the surface water is calm, it influenced the water level regime. During last 15 years, the amplitude of wind-induced water level fluctuations did not exceed 2 m near the estuary, i.e. the amplitude decreased by 2 times.

4. Confluence of a Regulated River with a Tributary

At the confluence of two rivers or a river and its tributary, one observes their mutual influence on the hydrologic regime. Regulation of a river drastically alters the effect of its still unregulated tributaries on its regime. The correlations between the flow of a river and the corresponding flow of its tributaries are altered. The lower reaches of the tributaries change from back-pressure into "non back-pressure" sectors (according to N.I. Makkaveyev's terminology).

In areas where the river merges with its tributaries, the most significant changes in hydrologic regime occur during the flood period, when the reservoir is being filled and its water flow decreases by several times, while the flood flow of the tributaries remains unchanged. Before regulation of a river its flow exceeded, as rule, the flow of its tributary during the entire flood period, but after regulation the flood flow of the tributary exceeds the flood flow of the river during dry and medium dry years. For example, at the confluence of the Vilyuya River with its tributary the Markha River, before Vilyuysk HES was built, the relationship of the flood flow of the river, (Qp), to those of the tributary, (Qrp), varied within 1.5 to 7.0 limits, while the maximum value of the Qp/Qrp ratio was 15. After flow regulation, of the Vilyuya River, this ratio decreased to 0.3-0.7 i.e. Qp became smaller than Qrp, and only during especially water rich years can Qp:Qrp reach 4.

During copious water years, at the beginning of the spring flood, the water flow of the tributary exceeds that of the main river and only during the second half of the flood period does the river flow become larger than that of the tributary. The influence of the a stream flow on the regime of its tributary and the low-water regime is characterized by the increased back-up of water in the lower reaches of the tributaries.

Based on a summary of a detailed analysis of long term hydrologic observations made in sectors of the Volga and Oka and at the Don and Severskiy Donets confluences, and based on special analytic and laboratory studies of these sectors made by Lengiprorechtrans, Gor'kiy Institute of Water Transport Engineers, TsNIIEVT, and the Transportation Services of the Don and Volga Basins, the following basic conclusions are made about the influence of flow regulation on the regime of a river and its tributaries in regions of their confluence.

After regulation of a river, the gradients in the sectors above the confluence with its tributary decrease considerably due to river waters backed up by waters of the tributary. At the same time, in the lower sector of the tributary, gradients increase toward its mouth. Figure 9 shows curves of the free surface of the Don and its tributary Severskiy

Donets before (solid line) and after (dashed line) Don flow regulation.

Figure 9. Curves of free water surface
along the Don River (1) and
its tributary Severskiy Donets
(2) before (solid line) and
after (dashed line) regulation
of its flow.
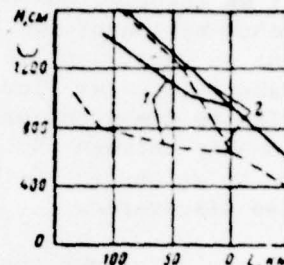
Comparing the two curves of the Severskiy Donets, one should note their
divergence due to a sharp increase in the water surface gradient toward
the mouth. Because of this decrease in water level, one sees that the
tributary stream narrows, and is confined to the low-water channel even
during large water flow. Consequently, the speeds of flow in the tributary
increase several fold causing an increase in stream competency, and makes
navigation more difficult. In the lower reaches of the Severskiy Donets,
velocities presently reach 3.5 m/sec during the spring flood, while in the
Samara River sector, a Volga tributary below the Kuybyshev HES, the flow
even reaches 5.5 m/sec according to P.A. Lisovskiy. No such large flow
velocities existed in the above sectors before flow regulation. The spring
flood usually begins earlier in the tributaries than in the main river.
After regulation of the main river flow the flood wave moves faster along
the tributary and reaches its mouth earlier because of the increase in tri-
butary gradients. The earlier arrival of tributary flood waters in a regu-
lated river causes the decrease in the flood water temperature.

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Figure 10. Graph of the relationship
$Z = f(Q1/Q2)$ based on
observations on the Volga
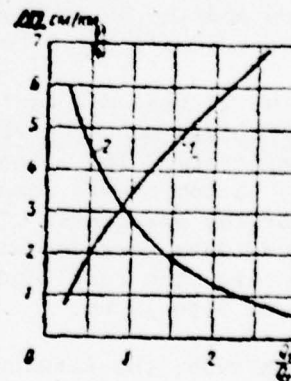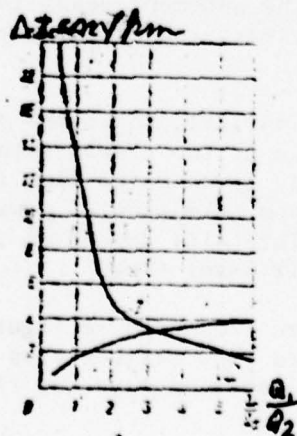(1) and Oka river sector
(2) above their confluence. $\longrightarrow$

$\longleftarrow$ Figure 11. Graph of the relationship
$Z = f(Q1/Q2)$ based on
observations on the Don
(1) and Severskiy Donets
(2) sectors above their
confluence.

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Analysis of gradient changes in the confluence sections of a number of tributaries (Volga and Oka, Don and Khoper, and Don and Severskiy Donets), as well as calculations by the author in 1956 for a theoretical model of a confluence region of two rivers with a prismatic bed, indicate that the gradient on short sectors of these rivers is functionally related not to their absolute water flow values, but to their ratio, i.e. $Inp = f(QP/Qrp)$, where Inp is the gradient in the lower sector of the tributary. An inverse relationship between the amplitude of the gradients on the different rivers and the relationship of the maximum flood flow of the river and its tributary was also discovered.

Figure 10 graphs the dependence of mean water level decrease (ΔZ) on the relationship between the water flow of the Volga (1) and Oka (2) in the sectors above their confluence. The amplitude of the mean variation in water level decrease on the Volga and Oka is practically identical when their maximum flood-period flow values are approximately equal and are 1 to 6 cm/km. A similar phenomenon is observed at the confluence of the Don with the Khoper. However, at the juncture of the Don with Severskiy Donets, where the maximum flood flow is approximately 5 times smaller than that of the Don, the amplitude of the mean variation in water level decrease of the latter is (fig. 11) 0.5 to 4.0 cm/km, while on the Severskiy Donets it is 2 to 20 cm/km (i.e. 5 times that of the Don).

The channel (bed) gradient usually is greater in the tributaries than in the river into which they flow. Consequently, the back water zone created on the tributary of the main river at a given value of river-to-tributary water flow ratio (Qp/Qrp) is shorter than the back-up zone created on the river by the tributary at a similar Qrp/Qp ratio. For example, when the ratio of the Don water flow to that of the Severskiy Donets is 10 to 12 and the absolute Don water flow is 7,700 m^3/sec (1951), water backed up on the Severskiy Donets for 30 to 40 km. At the same ratio of the Severskiy Donets flow to that of the Don and the Severskiy Donets flow of 3300 m^3/sec (1953), the Don waters were backed up for 110 to 120 km above the Severskiy Donets confluence.

The increased competence of the spring flood flow in the sector above the tributary mouth carries a large quantity of detritus into the river below the tributary. The larger sediment fractions, which are quickly deposited on the bottom, create local sediment accumulations that cause some redistribution of the gradients. In the tributary sector immediately above the confluence, the gradients decrease somewhat because the sediment deposits back up the water, while below the confluence on the main river, the slopes increase for a distance of 5 to 10 km.

In 1956, the Estuary Laboratory of TsNIIEVT, under the direction of A.I. Losiyevskiy, studied a model of confluence of two rivers with different confluence angles and different ratios of the river water flow (Qp) to tributary water flow (Qrp). These studies showed the formation of powerful vortex currents in the confluence, whose dimensions and intetsity depend on the angle of juncture of the streams and the ratio of their water flow.

Results of the laboratory studies are presented in figure 12, which shows plan views of the model with surface flow trajectories and sediment deposits. The greater the angle of confluence between the river and the

tributary the greater is the lateral compression of flow in the river
channel below the tributary and the greater the intensity of vortex current
formation where sediment introduced by the tributary is deposited.

Figure 12. Plan view of the
surface flow tra-
jectories and sed-
iment deposits for
different angles of
stream confluence
and water flow
ratios (model).
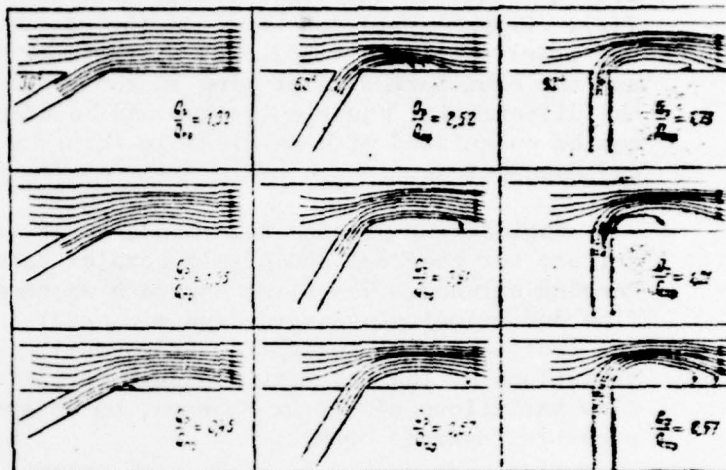
The preliminary laboratory tests were confirmed by experiments carried
out in 1955 on a model of the Volga and Oka junction under the leadership
of A.K. Pyazoke at the laboratory of the Gor'kiy Institute of Water Trans-
port Engineers. However, the vortex currents are different in the more
complex stream junctions with braided channels.

Figure 13 shows the location of vortices in the junction of the
Severkiy Donets and Don corresponding to different ratios of their discharges
based on data of the 1953 river channel studies. Comparing figures 12 and
13, one can see that in simple junctions (such as the confluence of the
Oka and Volga) the variation of the water discharge ratio of the merging
rivers causes variation of the vortex dimensions and corresponding shifts of
the vortex boundary across the width of the river during the flood period.
However, in complex junctions, in addition to the changes in dimensions and
direction of the vortices, there are also quantitative and qualitative changes
in the process. The formation of complex vertex currents at stream junctions   27
makes navigation very difficult, especially where channels branch and vortices
can affect almost the entire width of the river. These difficulties are
caused by the vortex currents and the large amounts of detritus deposited in
the navigation channel.

Figure 13. Plan views of surface current flow lines in the Severskiy Donets
estuary corresponding to different ratios of Don and Severskiy Donets flow.
(Figure is illegible and will not reproduce).

The phenomena discussed above, which occurs at the confluence of tribu-
taries with a regulated river, leads to the conclusion that one of the most
important factors determining the hydrologic regime of such a river are the
tributaries. The role of tributaries is even more important, because they
change the sedimentation and thermal pattern of the stream flow. Recognizing
the practical importance of evaluating changes in a river's hydrologic regime,

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we recommend calculations of the water level regime expected after flow regulation of the river sectors above the confluence.

Initial conditions for each sector can be determined from the relationship $Q = f(t)$ in the river confluence, as well as from the relationship $Z_0 = f(s)$. Common conditions for all the sectors are the unique water level at the point of stream confluence at any moment in time $Z_1 = Z_2 = Z_3 = f(t)$ and the equilibrium water flow in the confluence $Q_1 + Q_2 = Q_3$. Analysis of the differential equation system and boundary conditions indicates that they can be calculated with permissible accuracy only under certain limitations and assumptions.

Engineering pratice recommends three simplified approaches that substitute for the real and highly complex and unstable movement of the two merging streams. The first approach assumes that the variations in water flow and velocity pressure (dynamic head) in all three sectors adjacent to the conlfuence are insignificantly small; the second approach considers variations of the velocity pressure (dynamic head), while the third includes flow variations along the channel, but disregards variations of the velocity pressure (dynamic head).

In order to eliminate the influence of the morphologic features peculiar to individual rivers during evaluation of these calculation methods, preliminary verification was achieved using a theoretical model of a prismatic river channel with hydrologic and morphologic features similar to these of plain river channels of the Soviet Union. The results of these theoretical calculations indicate that, considering the unstable stream flow on short sectors (10-30km), and even with rather significant flow variations in time $(2Q/2t)$, can yield an insignificant correction of the water level. The inclusion of the velocity pressure variation in the calculations is necessary because the velocity pressure value can comprise 10 to 15% of the water level drop between the comptutation sections.

The verification makes it possible to recommend that calculations of the flood levels in the lower reaches should be made using N.N. Pavlovskiy's graphic method for steady-state flow and constructing the $I = f(z)$ graph from hydrometric data according to A.N. Rakhmanov's method [93]. This method has certain advantages under these conditions, because the lower stream sectors frequently contain hydrometric cross sections (stations), usually had satisfactory navigation conditions before flow regulation, and the topographic data are insufficient. For construction of the $I = f(Z)$ graph, one can use water level data from gauges on the boundaries of the sector, and information on water flow at the nearest hydrometric gauges. The $I = f(Z)$ graph constructed from hydrometric data automatically incorporates the effect of the velocity pressure along the sector.

5. Sediment Load

On rivers regulated by large water reservoirs, variations in the sediment load results from deposition in water reservoirs and increased competence of the tributaries during the spring flood. Analysis of the sediment load from water samples taken in the Polyana Frunze hydrometric section, situated on the Volga 59 km below V.I. Lenin Volzhskaya HES, indicated

that, after flow regulation in 1956-1962, the mean annual turbidity of the stream decreased, compared to the 1935-1955 period, from 77 to 83 g/m^3 to 15 to 31 g/m^3, i.e. to approximately one-third, although the annual water flow (volume) remained unchanged. Such a decrease in stream turbidity after flow regulation is caused by sediment deposition in the water reservoir and indicates that the stream picks up sediment very slowly during the first several tens of kilometers below the reservoir.

Farther downstream turbidity again increases and at the Lebyazh'ye cross section, 913 km below the V.I. Lenin HES, mean annual turbidity decreased only 10 percent after flow regulation. On the Don River, at the Razdorskaya cross section located 150 km below the Tsimlyansk HES, mean annual turbidity decreased only 4% (from 182 g/m^3 to 175 g/m^3) after flow regulation. In this case, one must consider that the Razdorsk section is below the Severskiy Donets (Don tributary). However, flow regulation has relatively little influence on the amount of turbidity, but causes significant changes in the seasonal distribution of the sediment burden.

Table 3 presents Hydrometeorologic Service observation data on the monthly suspended sediment load at the Verkhne-Lebyazh'ye hydrometric section on the Volga (446 km below the XXII Congress of KPSS HES) and at the Razdorsk hydrometric section on the Don.

Table 3

Hydrometric section	Periods	Monthly Average sediment load, kg/sec												Annual mean monthly 10за
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
Verkhnyaya	1947--1955	26	31	57	830	3100	810	266	110	83	130	140	24	467
Lebyazh'ye	1956--1962	78 78	98	122	581	1755	1035	254	121	138	102	97	39	368
Volga R.														
Razdorskaya	1945--1951	8	35	365	705	425	44	15	9	7	6	7	7	136
Don R.	1952--1958	170	240	190	645	145	44	35	32	27	24	25	20	128

It follows from table 3 that after flow regulation, the sediment load increased significantly in winter and during the summer dry season, but decreased during the spring flood, i.e. monthly variation in sediment burden decreased. In this respect, the changes in the sediment load regime caused by regulated flow in the Volga and Don are similar. However, the annual sediment discharge of the Volga decreased by 20%, but only 5% in the Don. This difference is explained by the morphologic features of the

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two river systems; tne lower Volga, unlike the lower Don, has no large tributaries.

More thorough analysis of the sediment flow regime in selected years before and after regulation of the water flow indicates that the sediment burden increases unevenly and abruptly at the months of tributary streams.

Figure 14. Graphs of water flow (solid line) and sediment load (dashed line) variations during the 1953 spring flood at the Razdorsk hydrometric section on the Don.
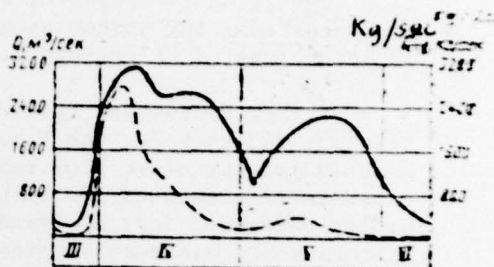

Figure 14 is a graph of variations in water flow and sediment burden during tne 1953 spring flood at the Razdorsk hydrometric section on the Don. In spring of that year the spring floods on the tributary and the river occured at different times. The first water flow peak in April was caused by the flood on the Severskiy Donets, when the water flow through Tsimlyansk Dam was only 10% of that of the Severskiy Donets. The second peak in May resulted from the increased water discharge from Tsimlyan reservoir. By this time, the flood on the Severskiy Donets had passed, and the water flow of this river decreased to 10 to 15% of the Don flow. The duration and maximum water flow of the first and second flood waves differed by only 1.5 times. However, during the first flood wave, the sediment load was almost 7 times that of the second flood wave. Such a difference is due to the different origins of the two flood waves and demonstrates the large role of the sediment carried by the tributaries.

The data in table 4 show the mean monthly water flow and sediment load during 1963 at two hydrometric sections of the lower Don; Nikolayevsk located 65km from the dam and above the month of the Severskiy Donets and Razdorsk section below the Severskiy Donets confluence. Correlations of the mean annual water flow at the downstream and up stream cross sections is 1138/793 = 1.43, while that of the sediment load is 180/58 = 3.10.

Table 4

Sections	Monthly water discharge, m³/sec (numerator), and sediment load, kg/sec(denom.)												Mean
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
Nikolayevsk	261 / 5.2	184 / 4.1	200 / 7.8	530 / 50	3660 / 430	1400 / 56	705 / 32	615 / 27	611 / 25	606 / 24	614 / 22	454 / 13	793 / 58
Razdorsk	337 / 10	395 / 95	684 / 160	2180 / 1100	4450 / 530	1480 / 64	810 / 51	702 / 38	678 / 27	699 / 27	728 / 22	516 / 13	1138 / 180

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Table 5 presents detailed data on the water flow and sediment load during spring flood periods for a number of years before and after flow regulation on the hydrometric sections. Analysis of table 5 data makes it possible to identify some features of the sediment load regime during the spring flood.

During regulation of the river, the volume of suspended sediments does not decrease proportionally to the spring flood flow, but decreases less than the latter, consequently increasing the mean turbidity of the stream. The increased turbidity is caused exclusively by the tributary flow, whose mean turbidity during the flood has increased from 300 to 500 g/m^3 (i.e. by 70%) after regulation of the Don, while the mean turbidity of the Don River above the Severskiy Donets decreased from 210 to 130 g/m^3, i.e. by 38%. Consequently, after regulation of the river flow the relationship between the sediment load of the river and the tributary changes more drastically than the relationship between their respective water flow. Before flow regulation, the spring flood flow of the Severskiy Donets averaged 18% of the overall Don flood flow and 24% of its sediment load, while after regulation of the Don the contribution of the Severskiy Donets to the water flow increased to 35% (twofold) and its proportion of the sediment load increased to 67% (amost threefold).

Graphs of the relationship of the sediment load (W_{TB}) to the overall water flow (W) before and after regulation were constructed from table 5 data (fig.15). One can see that after flow regulation the ratio changes at a regular rate. Average turbidity of the stream during the flood period increases in most cases and decreases only during extremely dry years.

Figure 15. Graph of the relationship $W_{TB} = f(W)$ for the Razdorsk hydrometric section of the Don before (solid line) and after (dashed line) flow regulation.
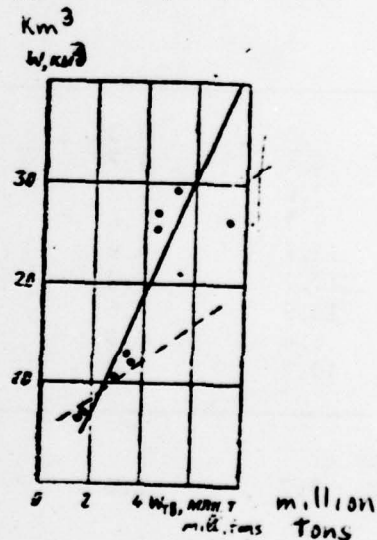
From table 5, one can also see that after the regulation of the river flow the monthly fluctuation range of the sediment load and mean turbidity values of the flood flow increased in the river section below the inflow of the large tributary. Correlation of the maximum and minimum spring flood sediment burden was 4.7 (7.6:1.6) before regulation and increased to about 28.5 (5.7:0.2) after regulation, because of the decrease of the minimum sedi-

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Table 5

Year	Don R. Razdomorsk hydrometric section			Severskiy Donets, Belaya Kalitva hydrometric section		
	Water flow W (km^3)	Sediment load WTB (10^6 tons)	Mean Turbidity (y/m^3)	Water flow W (km^3)	Sediment load WBT(10^6 tons)	Mean Turbidity (g/m^3)
1938	11.1	2.7	240	1.4	0.03	20
1939	12.1	3.6	300	3.1	1.4	450
1940	23.7	7.4	310	6.0	2.8	470
1941	39.4	6.8	170	7.9	2.2	280
1947	24.9	4.3	180	5.4	1.2	220
1948	26.4	4.2	160	1.8	0.3	170
1949	8.6	2.0	230	1.5	0.3	200
1950	6.9	1.6	230	1.7	0.2	140
1951	24.9	7.6	300	4.2	1.8	430
Mean for the section	19.8	4.5	230	3.6	1.1	300
Mean above tributary (month)	16.2	3.4	210	---	---	---
1952	4.5	3.3	730	2.7	3.2*	1180
1953	14.4	5.7	390	4.6	4.8*	1040
1954	3.6	0.2	60	0.8	0.04	50
1955	9.7	1.6	170	4.2	1.0	240
1956	13.7	4.9	360	4.3	1.8	420
1957	10.7	1.3	120	3.1	0.8	260
1958	13.9	3.6	260	4.2	1.9	450
1959	6.4	0.8	130	2.0	0.5	250
1960	10.5	2.0	200	4.3	1.6	360
Mean for the section	9.7	2.6	2/0	3.4	1.75	510
Mean above tributary (month)	6.3	0.85	130	---	---	---

* Sediment load for these years was measured at the Severskey Donets lower reaches

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ment load. In addition, after flow regulation, the maximum turbidity of the flood flow in individual years can be triple the mean value. Before flow regulation, the maximum turbidity was not more than 35% more than the mean value.

As already mentioned above, the dry-season sediment load increases after regulation of the water flow; at the same time, the sediment load 33 increases approximately proportionally to the increase in water flow, i.e. dry-season turbidity remains at the regulation level. Analysis of the turbidity of water samples made during the dry season in different river sectors indicates that the stream, flow whose turbidity was reduced by deposition in the reservoir, increases again over a distance of several tens of kilometers below the dam. On rivers characterized by stable (non-eroding) banks, the section where the stream becomes saturated with the increase in turbidity (sediment load) migrates down stream after several years of flow regulation. This is attributed to building up of the bottom of a regulated river and the decreased slopes in the sector below the dam.

Evaluation of the sediment load of the lower section of a tributary stream is important in constructing hydraulic works on regulated rivers. Given below is a condensed plan for approximate calculation of the sediment load of a tributary based on a hydrologic regime prognosis for an expected spring flood.

To prepare data for the calculations, one must first analyze the water level regime and calculate the coordinates of the $Irp = f\ Qp/Qrp$ curve. The following method is used to construct computation graphs of $Q = f(t)$ for sections of the river and the tributary. When the spring flood flow prediction is made well in advance, one determines the overall volume of water released through the dam, (W) and its duration (t flood) are determined. The river flow (Qp) during the spring flood is assumed to be constant, i.e. $Qp = W$ released: t_{flood} during the spring flood. When the forecast for the tributary is also made well in advance, the hydrograph $Om + f(t)$ of the same reliability as the long term flood volume is used for the calculations. Naturally, the calculations of hydrographs of different reliability and construction of long-term flow reliability curve must be made in advance.

When the forecast for the tributary is not reliable enough to evaluate the sediment load the $Qpr = f(t)$ graph is constructed from the maximum frequency, individually for each phase of the flood. The closer the $Qpr = f(t)$ curve, constructed by this method, is to the actual curve, the smaller is the fluctuation of the spring flow maximum.

The relationship $Ipr = f(t)$ of the equation is based on $Q = f(t)$ graphs for the river and tributary and the $Ipr = f(Qp/Qpr)$ curve. Using the $Ipr = f(t)$ relationship as well as data on variation of the river' channel width B depending on the water level (z) $\overline{B} = f(z)$, one determines the hydrologic parameters for each interval of the flood: hydraulic radius 34 R, Chezy factor C, and flow speed V.

Assuming that in each comptutation interval, the stream movement is stable and even and the channel roughness value is constant (n=const.),

one can write the following for two moments of time t_1 and t_0:

$$Q_0 = \frac{B_0 R_0^{5/3} \sqrt{I_0}}{n} \qquad (1)$$

$$Q_t = \frac{B_t (R_0 + \Delta R)^{5/3} \sqrt{I_t}}{n} \qquad (2)$$

For low values of $t = t_1 - t_0$ and a parabolic channel, one can reasonably assume that $R = 2/3 (\bar{Z}_t - \bar{Z}_0)$.

Dividing expression (1) by (2) and noting that

$$\frac{Q_0}{Q_t} \frac{B_t}{B_0} \frac{\sqrt{I_t}}{\sqrt{I_0}} = \frac{R_0^{5/3}}{(R_0 + \Delta R)^{5/3}} = M,$$

We find

$$R_0 = \frac{\Delta R M^{3/5}}{1 - M^{3/5}}$$

and then find n, Co, and Vo by using generally accepted equations. Based on original data and using A.V. Karaushev's equation $Ps = 1.34 \times 10^{-7} \frac{NV3.75B}{W0.75}$ for example, one can determine the flood period mean sediment load as a sum of the sediment load of intervals $\bar{W}_{TB} = \sum_{to} P_{si} \Delta t_i B_i$.

Sample calculation. This problem deals with the sector of the Severskiy Donets above its confluence with the Don under average flood conditions for this river and minimal frequency of use of the Tsimlyansk dam navigation locks, i.e. Qp = 400 m3/sec. The flood period is 40 days. For calculation purposes it is subdivided into 8 five-day intervals. Values of Qz for each interval have been determined from the flood hydrograph with a probability of 50% and some rounding off.

Slopes were determined using the $I_{2pr} = f(Q_{pr})$ curve constructed from observed data for the lower reach of the Severskiy Donets (fig. 15) The mean water elevation for each interval has been determined by calculation of $\bar{Z} = Z_3 + \frac{\partial Z}{2}$, where Z_3, the water level in the lower sector, was calculated from the $Q_3 = f(H)$ graph, while $\bar{Z}$ was obtained from calculated values of I_2 and the distance between the hydrometric sections. The values of $\bar{B}$ were also determined from the previously constructed $\bar{B} = f(\bar{Z})$ curve. The mean diameter of river channel bottom sediment particles, d = 0.5 mm, and mean water temperature, t = 5°C, were used in the calculation.

All the calculated data have been compiled into a table (table 6).

Table 6

Inter-val	Qp	Qpr	I_{2pr}x 10^{-5}	$\bar{Z}$	$\bar{B}$	ΔR	R	v	C	P_s x 10^{-6} (m3/sec)	$P_{si} \Delta_i B_i$ (10^4 m³)
1	400	800	18	6.60	170		3.08	1.53	65	2344	172.0
						+0.87		1.93	67	5888	535.0
2	400	1600	21	7.90	210		3.95				
						-0.27					
3	400	1300	20	7.50	195		3.68	1.81	66	4467	376.0
						-0.60					
4	400	800	18	6.60	170		3.08	1.53	65	2344	172.0
						+0.27					
5	400	1000	19	7.00	180		3.35	1.63	65	2951	223.0
						-0.27					
6.	400	800	18	6.60	170		3.08	1.53	65	2344	172.0
						-0.34					
7	400	600	15	6.10	160		2.74	1.37	67	1514	105.0
						-0.40					
8	400	400	13	5.50	150		2.34	1.14	65	725	47.0
											1802.0

Comparison of the calculated flood sediment load for the lower sector of the Severskiy Donets with actual values for a series of years (table 5) indicates that the proposed method guarantees acceptable accuracy by calculations.

Finally, one should note that during the first year after flow regulation by the reservoir, usually no flood waters are released while the reservoir is filled to capacity. Only during extremely rainy years can excess flood water be released, but in such cases it usually is released after passage of the floods down the tributaries. Consequently,

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for the first year Qp is usually constant (Qp = const.) and does not exceed the minimum permissible value required for the maintenance of navigational and sanitary needs.

6. Variation of the Temperature Regime of a Stream

Variation of the temperature regime of a stream below the water reservoir is controlled by the specific thermal regime of the reservoir. During last decade, great attention was given to the thermal regime of water reservoirs and this problem has been well enough studied at the present time. Agencies of the Hydrometerological Service made multifaceted in situ investigations in a number of water reservoirs. The thermal features of Tsimlyan Reservoir have been studied most thoroughly. Summarizing the results of these studies, the following features of the thermal regime of large water reservoirs can be listed briefly.

When ice formation begins, the water temperature in the reservoir begins to rise gradually - in a thin layer at the bottom, at first, and then extending upward. This process is unstable in time, and continues with constantly increasing intensity during the second part of the winter. Toward spring, the water temperature becomes relatively homogeneous in the vertical direction and then, after passing the critical point (4°C) the surface temperature begins to exceeds the bottom temperature. As the overall water temperature rises during the early summer, the difference between surface and bottom temperatures increases and reaches 5 to 7° C. Subsequently, during the overall water temperature decrease toward the autumn, the temperature difference with depth gradually disappears and the temperature again becomes vertically homogeneous. The chonological order of variation of water temperature distribution with depth in the lower (dam vicinity) zone of a water reservoir is presented in fig. 16.

Figure 16. Temperature distribution with depth in the lower dam zone of Tsimlyan Reservoir during different seasons of the year: 1-winter, 2-spring, 3-summer, and 4-autumn.
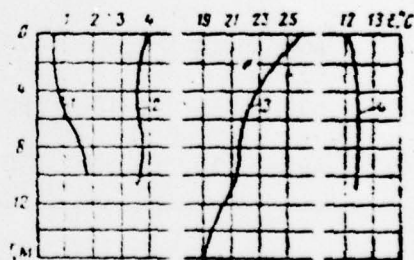
During the study, it was established that the vertical homogeneity of the water temperature in a water reservoir is due to wind action. Consequently, in shallow (upper) sectors of a reservoir, where wind waves affect a greater part of the water column, spring heating and autumn cooling occur more quickly. In these reservoir sectors, temperature fluctuations correspond more closely to air temperature fluctuations. On the other hand, in deep sectors of reservoirs, the water warms and cools more slowly in spring and fall, and air temperature fluctuations influence only the surface water temperature.

Because of the difference in the spring temperature regimes of shallow and deep-water sectors of reservoirs, the surface water temperature varies over a reservoir and increases from the lower (dam) end to the upper part of the reservoir (fig. 17a). On the other hand, in the autumn, the surface water temperature decreases from the lower (dam) end the upper sector (fig. 17b). Because of this vertical and horizontal temperature distribution in a reservoir, the temperature difference between surface and bottom water in the deep dam sector is especially significant and stable in summer (fig. 18).
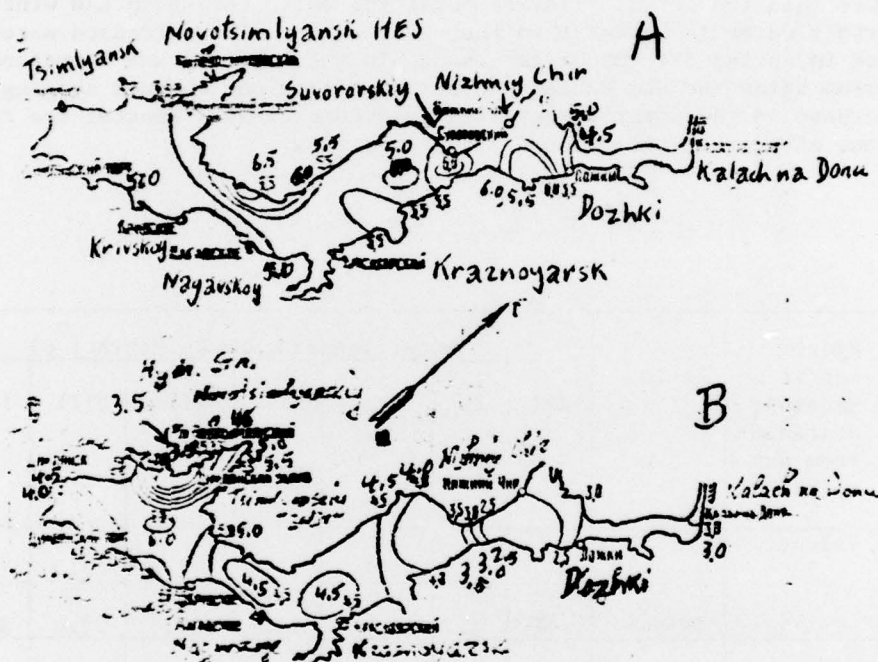
Figure 17. Distribution of surface water temperature in a reservoir: a - spring, b - autumn.

Observations in other reservoirs indicate that their water temperature variations are similar during the navigation period. However, quantitative vertical water temperature variation depends to a considerable extent on the rate of water release from the reservoir.

Figure 18. Graph of water temperature variation in the lower (dam) zone of a reservoir: 1-surface T, bottom T.
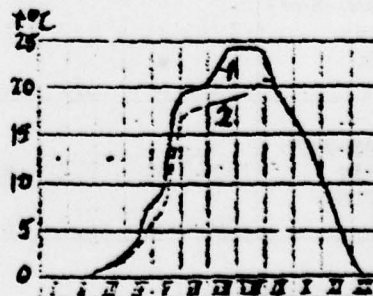
B.S. Borodkin's studies of Gor'kov water reservoir
established that during a transient speed of flow (u) of the order of
0.15 to 0.20 m/sec, the difference between the surface and bottom water
temperatures in winter at a depth of 15m was only $0.36^{o}C$.

Below dams, the water temperature regime has its own characteristic
features. The water leaves the dam through openings located below the normal
water level in the reservoir, and the temperature of the (released) water
is that of the deep water layers of the lower (dam) end of the reservoir.
Consequently, in spring and summer the water temperature below the dam is
lower than the normal river temperature, while in autumn and winter the re-
servoir water is warmer than the river water. The decreased water tempera-
ture in spring determines the change in the capacity and competence of the
stream below the dam during the period of maximum channel shaping, while the
increase in the water temperature in autumn creates special ice regime condi-
tions after the regulation of the river flow.

Table 7

River and Dam	Hydro-metric Section, distance from dam (km)	Period	Water Temperature by Month (^{o}C)								
			III	IV	V	VI	VII	VIII	IX	X	XI
Volga XII Congress of KPSS HES	Volgograd 20	1951-58	---	1.8	9.6	19.0	22.4	22.2	17.2	9.6	2.3
		1959-64	---	2.2	8.5	17.3	21.6	22.0	18.2	13.1	6.1
Volga XII Congress of KPSS HES	Astrak-han' 600	1951-58	0.1	3.9	12.3	20.2	23.9	23.7	19.0	11.3	3.4
		1959-64	0.4	4.7	10.9	19.3	23.4	23.1	18.6	12.5	5.6
Volga Gorkov-skiy	Bolakhna 30	1946-55	---	1.4	10.5	18.1	19.8	18.5	13.2	5.9	0.7
		1957-63	---	0.9	9.2	16.2	19.7	18.9	13.7	7.3	2.0
Don Tsimlyan skiy	Kamyshev-skiy 30	1945-51	0.2	7.5	16.3	22.1	23.1	22.4	17.3	8.8	3.0
		1952-58	0.9	4.9	12.5	19.0	22.0	22.6	18.7	13.0	5.1
Don Tsimlyan-skiy	Bagayev-skiy 200	1945-51	0.8	8.3	16.4	21.8	23.1	22.1	17.9	8.7	3.5
		1952-58	0.7	6.7	14.5	20.1	22.8	22.7	18.4	12.4	4.4

Analysis of long term water temperature data for a series of Don River sectors below Tsimlyan reservoir and the Volga River sectors below Gor'kov and Volgograd reservoirs indicates that after flow regulation, the spring-summer water temperature decreased, not only directly downstream from the dam, but also over long stretch of the river below the dam. Table 7 presents long term data on spring, summer, and autumn mean water temperature of the Volga and Don hydrometric sections near and far from the dams for year before and after regulation of the river flow.

Mean long-term water temperature curves before and after flow regulation were constructed for two hydrometric sections on the Don River - Kazan section above Tsimlyan Reservoir and the Kamyshev section below the dam (fig. 19). These curves show that on the unregulated part of the river (Kazan hydrometric section), water temperature variation after flow regulation almost coincides with that existing before flow regulation, whereas on the regulated part of the river (Kamyshev hydrometric section), a definite water temperature variation phase shift was caused by the regulating action of the reservoir.
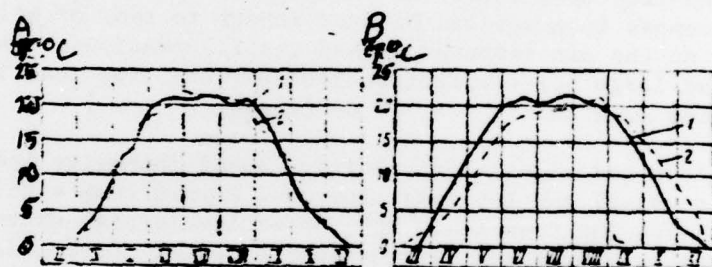

Figure 19. Long term water temperature variation curves: a - above the reservoir; b - below the reservoir; 1 - before flow regulation; 2 - after flow regulation.

One should note that the present method of measuring water temperature variations on hydrometric sections on the banks does not guarantee reliable data on the true mean temperatures of a stream and the water temperature distribution over an entire channel cross section. B.A. Apollov [4] and A.B. Ogiyevskiy [62] using the observations on the Svir', Angara, etc.), show that water temperature in the rivers seems to vary greatly with depth and across the stream. Taking into account that the hydrometric sections of the Hydrometeorologic Service usually are located in deep troughs with low speeds of flow, while temperature measurements are made on the banks, one must assume that the real difference in the water temperatures of stream before and after regulation of its flow is considerably larger than indicated above.

Water temperature variations near the bottom are of the greatest interest in studying channel forming processes. Increased depth of river resulting from its flow regulation caused, it seems, an increase in the difference between the bottom water temperature and the temperature measured on the bank at a hydrometric section.

While investigating water temperature variation in rivers, the author noticed the monthly consistency of water temperature variation curves in the spring, if the date when the river becomes free of ice is taken as the beginning of spring. The range of the mean ten-year water temperature values does not exceed $\pm$ 3°C according to   hydrologic almanacs. Exceptions are south-to-north flowing rivers, such as the Severnaya Dvina, in which the scattering of the points on the (curve) increases about 4 weeks after the river is free of ice.

During autumn and winter the water temperature below the outlet of a large reservoir is higher than natural; this creates a considerable open water lead that extends downstream from the dam. K.I. Rossinskiy studied this phenomenon in detail in the river sector below the Rybin dam [34] and developed thermal calculation methods   that are applied in designing river hydraulic works. Without repeating Rossinskiy's conclusions, we present below a condensed summary of experience with the outlets of other water reservoirs, as well as the author's observations on the lower Don.

Ice forms on a regulated river in the same way as on free rivers, but a lead (ice-free open water) is formed directly below the dam. In winter the lead ranges from several hundred meters to tens of kilometers in length, depending on the air temperature and its fluctuations. During constant warming and large air temperature fluctuations the lead increases in area while during constant frosts, it decreases.

Constant and significant cooling causes intensive ice formation in the lead (open water) and ice jams along the down-stream edge of the lead. For example, below the Kremenchug HES, water levels rise up to 5m. The instability of the ice cover and fluctuations of water level create difficulties for the populated places and industrial centers near the dam. During significant cold spells, bottom ice ("shuga") is formed downstream from the lead. Movement of this ice downstream by the river current causes winter erosion of the channel downstream.

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During the second half of the winter, as the water temperature in the deeper water levels of the reservoir increases, the lower edge of the lead begins to retreat progressively from the dam section. Once started this longitudinal expansion of the lead continues, but at a slower rate, even when the air temperature drops below 0°C. Just before the general breakup, the ice retreat rate can reach 10 to 15 km/day.

Observations on the lower Don indicate that the determining factor in the extent of the ice edge retreat from the dam is the amount of water discharged and not the air temperature, although the influence of the latter is also undisputable. Just before general river-ice breakup, the length of the lead (open water) is only 35 to 50 km if the water discharge is 100 to 150 m3/sec, but it reaches 250 to 270 km when the water discharge is 1000 to 1200 m3/sec.

On regulated rivers, the spring ice run progresses generally more calmly than on unregulated rivers. However, at tributary months and in lower reaches of the tributaries of regulated rivers, the ice run progresses very turbulently

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and the probability of ice dams increases because the ice breakup may occur earlier with the accompanying water level drop on a regulated river. On rivers where the construction of a series of dam has not been completed (for example on the Volga, near Cheboksar), ice dams also occur at the upper end of the reservoir as water backs up.

On regulated rivers, in spring, a peculiar situation occurs that delays the opening of navigation. After the ice run has ended on the river or its ice cover has been considerably weakened, the ice in the backed-up waters and in coves remains quite thick, retains its winter structure, and prevents boats from venturing out. In order to begin navigation early below the dams, the water areas of ship repair facilities should be located in an active river arm, but not too close to the dam, because systematically reccuring ice runs and ice jams are possible close to the dam in winter.

After the construction of reservoirs on a river to regulate water flow, navigation conditions of the river fleet change. The water is open for navigation longer in the sector below the dam, but the navigation season decreases in the reservoir. The freezing and breakup dates of the back waters and coves, which also determine the duration of navigation, do not change. On the regulated water routes of the central river basins (from Belomorsk, Leningrad, and Perm' to Astrakhan' and Rostov), as well as in the Dnieper Basin, the actual duration of navigation fluctuates sharply from year to year. At the same time, there is a significant difference between the breakup and freezing dates below the dams and in the reservoirs.

The difference between the above ice-run (breakup) dates is 30 days, while that between the freezing dates is a maximum of 20 days. At the same time, the difference between the dates of 30cm thick ice formation (limit for navigation) is only 10 days because the rate of ice accretion is influenced mainly by snow cover formation (which is not affected by the presence of reservoirs). One should also note, that the rate of ice accretion depends more on air temperature fluctuation than on its absolute values. After each warm spell, an increase in the ice accretion rate occurs; at the same time, if there are no warm spells, the ice accretion rate decreses rapidly and the total thickness of ice is less than that of a year with warm periods.

Certain brief conclusions can be drawn from the above.

When a river's flow is regulated by a large reservoir, the hydrologic regime of the river changes regularly along its entire length in comparison to the regime prior to regulation of the river.

The annual water flow curve shows less variation; flood flows decrease, while dry-period and, especially, winter flows increase.

Water surface levels and gradients also fluctuate less; they decrease during the flood and increase during the dry season. The frequency of dry season [water] levels increases.

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The annual flow curve becomes more even; the flow is less during the flood and is more during the dry period. During the flood, the sediment burden increases unevenly along the river length; the sediment load is concentrated in the inflow sectors of large tributaries. Turbidity of the flood flow in the sector above the inflow of the first large tributary is considerably less than normal, while in the sector below this tributary junction the turbidity is considerably higher. On rivers with regulated flow and no tributaries, the turbidity of flood current increases gradually with distance from the dam section.

During spring and summer the temperature of the river is lower than normal, while during autumn and winter it is higher. In comparison to normal conditions, the greatest decrease in stream temperature occurs during the first part of the flood. Below the dam, the freeze up occurs later than before   regulation, while the breakup (ice run) occurs earlier.   43

In addition to the above general regularities, individual local variations of the hydrologic regime occur on typical sectors of a regulated river. These variations include, for example, intensive fluctuations of flow velocity and water surface gradients in the sector immediately below the dam; these fluctuations are the result of the diurnal and weekly regulation of the flow by the HES.

At the point where a river meets its tributary a higher water level and greater current speed is observed on an unregulated river. In the lower reaches of a river after regulation its flow causes an increase in gradient and a reduction in the amplitude of the variation in water level.